Subaru Surveys for High-z Galaxies

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Abstract. We present a summary of optical/NIR deep surveys for very high-z galaxies using the 8.2m Subaru Telescope operated by National Astronomical Observatory of Japan. The prime focus mosaic CCD camera, Suprime-Cam, with a very wide field of view, $34' \times 27'$, allows us to carry out efficient optical deep surveys. In particular, the Subaru Deep Field project has provided us a number of Lymanα emitters beyond $z = 6$. We discuss the star formation history in the early universe based on this project.

1 Introduction

Since the discovery of Lyα emission from a galaxy at $z = 5.34$ [4], more than two dozen of Lyα emitters (LAEs) have identified spectroscopically; see for reviews, [27]; [23]. The most distant LAE known to date is SDF J132418.3+271455 at $z = 6.578$ [14]. Another very high-z LAE is HCM-6A at $z = 6.56$ [9]. These discoveries are actually thanks to the great observational capability of 8-10m class optical telescopes. Furthermore, the GOODS survey has provided a sample of very high-z Lyman break galaxies (LBGs) at $z \sim 6$, thanks to the high-quality imaging capability of the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (e.g., [8], [5], [24]). These exciting observations enable us to investigate the cosmic star formation history and mass assembly history in the early universe. In this review, we present a summary of recent deep surveys for very high-z (i.e., $z > 5$) galaxies based on the 8.2m Subaru Telescope.

2 Subaru Surveys for High-z Galaxies

2.1 The Subaru Deep Survey

The 8.2m Subaru Telescope [12] has seven instruments; see http://www. subarutelescope.org/Observing/Instruments/index.html. During the commissioning phase of three instruments (FOCAS, OHS/CISCO, and Suprime-Cam), these instruments team members organized a systematic deep survey using these three instruments to investigate high-z galaxies; the Subaru Deep Survey (SDS). All the observations were done during a period between 1999 and 2001. Their target fields are (1) the Subaru Deep Field (SDF) centered at RA(J2000) = $13^{\rm h}$ $24^{\rm m}$ $21.^{\rm s}38$ and DEC(J2000) = $+27°29'23''$, and (2) the Subaru XMM-Newton Deep Field (SXDF) centered at RA(J2000) = $2^{\rm h}$ $18^{\rm m}$ $00.^{\rm s}00$ and DEC(J2000) = $-5°12'00''$. The SDF is used to make a very deep imaging survey while the

SXDF is used to make a wide-field, medium deep one; see for the SXDF project, [20], & [17].

(1) NIR Deep Imaging Survey: Very deep J and K' images of the central $2' \times 2'$ field of the SDF were obtained with use of CISCO [15]. The integration times of the J and K' bands were 12.1 hr and 9.7 hr, resulting in 5σ limiting magnitudes of 25.1 and 23.5 mag (the Vega system), respectively. These data are used to investigate the NIR galaxy number count, colors, and size distribution; see also [30]. They also found a population of hyper extremely red objects (HEROs) with $J - K' > 3 - 4$ [29]. These deep NIR data were also utilized to investigate the diffuse extragalactic background light (EBL) [28]. They found that ~ 90 % of the EBL from galaxies were resolved in their deep NIR images.

This NIR data set was also used to construct a K'-selected galaxy sample, consisting of 439 galaxies for which both optical (B, V, R, I, and z') and NIR photometric data are available [13]. Comparing the star formation rate density (SFRD) at $z \sim 3$ for their K'-selected sample with those based on previous LBG surveys, they found that a large fraction of SFRD at $z > 1.5$ may come from a faint blue galaxy population.

(2) Optical Narrowband Deep Survey: One of narrowband filters, NB711 centered at $\lambda_{\rm C} = 7126$ Å with $\Delta\lambda = 73$ Å was used to search for LAEs at $z \sim 4.9$ [16], [22]. They found 87 reliable LAE candidates at $z \sim 4.9$, and then analyzed their luminosity function and clustering properties [16]. They also found a large-scale clustering of LAEs with a scale of ~ 20 Mpc $\times$ 50 Mpc [22].

(3) Optical Broad Band Deep Survey: In order to investigate photometric and clustering properties of LBGs at $z \sim 4 - 5$, optical broad band data of both the SDF and the SXDF, covering 1200 sq. arcmin in total were carefully analyzed by [17], [18]. They obtained a large sample of LBGs (2600 objects) at $z \simeq 3.5 - 5.2$.

Their analysis shows that the correlation lengths are $\simeq 4.1$ h_{100}^{-1} Mpc and 5.9 h_{100}^{-1} Mpc in co-moving units for all the detected LBGs at $z \simeq 4$ and $z \simeq 5$, respectively.They also found that a typical mass of dark matter halos hosting LBGs with $L > L^*$ amounts to $\sim 1 \times 10^{12} M_\odot$, being comparable to those of typical massive disk galaxies like our Milky Way.

Based on the CDM model, they also estimated the mass of dark matter halos which could form from such high-z objects. Since they obtained a mass range between $\sim 10^{13} - 10^{15} M_\odot$, they suggested that dark matter halos hosting high-z LBGs could evolve to groups and clusters in the local universe. On one hand, faint LBGs, LAEs, and K'-selected galaxies could evolve to present-day galaxies after experiencing a few merger events.

2.2 The Subaru Deep Field (SDF) Project

As outlined in the previous subsection, the SDS gave a number of important findings in the research field of galaxy evolution. This success seems to be attributed to the very wide-field of view of Suprime-Cam and excellent seeing conditions at Mauna Kea. In order to make the SDS much more fruitful, the

Subaru Telescope Office decided to promote big surveys using guaranteed observing time that each Subaru builder member has. Then they proposed two big surveys for the extragalactic research; (i) the Subaru Deep Field Project led by Nobunari Kashikawa, and (ii) the Subaru XMM-Newton Deep Survey Project led by Kaz Sekiguchi. As mentioned before, the latter project is aimed to carry out a wide-field (1 sq. degree), medium deep survey in collaboration with the XMM-Newton Observatory. Since the SDF is dedicated to a very deep search for high-z galaxies, we present a brief summary of the current status of the SDF. It is noted that a common-use, intensive program on "A Search for Lyα Emitters at $z = 5.7$ and $z = 6.6$" (Proposal ID = S02A-IP2; PI = Y. Taniguchi) joined to the SDF project.

(1) SDF2002: Thirteen nights were allocated to the SDF project in the semester S02A. In this semester, we performed a deep optical imaging survey using a narrowband filter ($NB921$) centered at $\lambda = 9196$ Å together with i' and z' broadband filters covering an 814 arcmin^2 area of the SDF. We obtained a sample of 73 strong $NB921$-excess objects based on the following two color criteria; $z' - NB921 > 1$ and $i' - z' > 1.3$. We then obtained optical spectroscopy of nine objects in our $NB921$-excess sample, and identified at least two Lyα emitters at$z = 6.541 \pm 0.002$ and $z = 6.578 \pm 0.002$, each of which shows the characteristic sharp cutoff together with the continuum depression at wavelengths shortward of the line peak.

These new data allow us to estimate the first meaningful lower limit of the star formation rate density beyond redshift 6 [14]. First, we estimate the total star formation rate of 73 LAEs in our photometric sample using the equivalent width of NB921 flux. Our follow-up optical spectroscopy found that two among the nine LAE candidates are real LAEs, it seems reasonable to assume that approximately 22% (=2/9) of 73 LAE candidates are real LAEs at $z \approx 6.5$ - 6.6; $f(\text{LAE}) \simeq 22\%$. If we assume that all the 73 LAE candidates are true LAEs at $z \approx 6.5 - 6.6$, we obtain nominally a total star formation rate of $SFR_{\text{total}}^{\text{nominal}} = 475 h_{0.7}^{-2} \ M_\odot \ \text{yr}^{-1}$. Adopting $f(\text{LAE}) \simeq 22\%$, we can estimate the total star formation rate, $SFR_{\text{total}} \simeq 0.22 \times SFR_{\text{total}}^{\text{nominal}} \simeq 105 h_{0.7}^{-2} \ M_\odot \ \text{yr}^{-1}$. Given the survey volume, 202,000 $h_{0.7}^{-3}$ Mpc^3, we thus obtain a star formation rate density of $\rho_{\text{SFR}} \simeq 5.2 \times 10^{-4} h_{0.7} \ M_\odot \ \text{yr}^{-1} \ \text{Mpc}^{-3}$. This observation reveals that a moderately high level of star formation activity already occurred at $z \sim$ 6.6 (see also [9]).

(2) SDF2003: Fifteen nights were allocated for the SDF project in the semester S03A. We made optical deep imaging and spectroscopy again, and finished our optical imaging survey. We obtained optical spectra of additional 18 LAE candidates using FOCAS, and thus we obtained a spectroscopic sample of 27 LAE candidates including our spectroscopy made in 2002. From our spectroscopy, we identify nine LAEs at $z = 6.50 - 6.60$. The remaining 18 objects are; nine single-line emitters, one [O II] emitter at $z = 1.46$, two [O III] emitters at $z = 0.84$ and $z = 0.85$, and six unclassified objects. The single-line emitters are either [O II] emitters at $z \sim 1.46$ or LAEs at $z \sim 6.6$. Much higher-resolution spectroscopy will be necessary to identify them unambiguously.

Since our new spectroscopy leads to a new value of $f(\mathrm{LAE}) = 9/27 \simeq 33\%$, we obtain a star formation rate density of $\rho_{\mathrm{SFR}} \simeq 7.8 \times 10^{-4} h_{0.7}\ M_{\odot}\ \mathrm{yr}^{-1}$ Mpc^{-3}. It should be reminded that we apply neither any reddening correction nor integration by assuming a certain luminosity function for LAEs. Therefore, this value should be regarded as a lower limit.

We also made follow-up spectroscopy of a small sample of very red objects in $i' - z'$ color, and then identified a new bright LAE at $z = 6.33$. This suggests that a number of LAEs may be found in such very red objects. Finally, we remind you that the data reduction of SDF data taken in 2003 is still underway.

2.3   Deep Surveys based on Common-Use Observations

(1) Lyman Break Galaxies at $z \sim 5$: [11] (Proposal ID = S00-017; PI = K. Ohta) made deep optical imaging of 618 arcmin^2 including the Hubble Deep Field-North to search for LBGs at $z \sim 5$. They found ~ 100 LBG candidates at $23.0 \leq I_{\mathrm{C}} \leq 24.5$ and ~ 300 LBG candidates at $23.0 \leq I_{\mathrm{C}} \leq 25.5$. These data were used to estimate the rest-frame UV luminosity function at $4.4 \leq z \leq 5.3$. They found that the UV luminosity density at this redshift range is lower by a factor of two than that at $z \sim 3$.

(2) Lymanα Emitters at $z > 5$: [2] (Proposal ID = S01B-051; PI = Y. Taniguchi) made a survey for Lyα emitters at $z \approx 5.7$ based on optical narrow-band ($\lambda_{\mathrm{c}} = 8150\,\text{Å}$ and $\Delta\lambda = 120\,\text{Å}$), and broad-band ($B$, R_{C}, I_{C}, and z') obser-
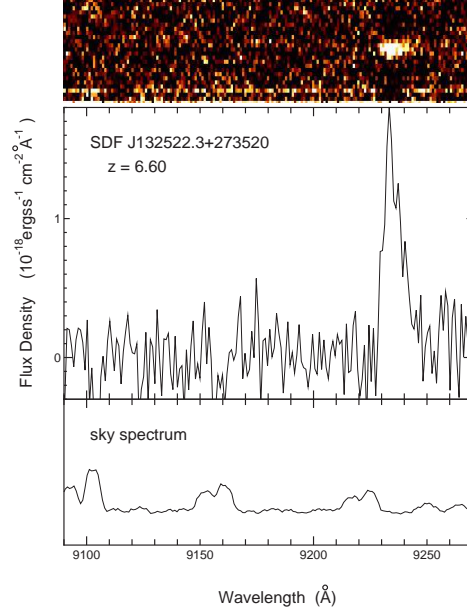

Fig. 1. The most distant LAE found in the SDF project; SDF J132522.3+273529 at $z = 6.60$.

vations of the field surrounding the high redshift quasar, SDSSp J104433.04−012522.2 at $z = 5.74$. This survey covers a sky area of ≈ 720 arcmin^2 and a co-moving volume of $\simeq 2 \times 10^5\ h_{0.7}^{-3}$ Mpc^3. They found 20 LAE candidates at $z \approx 5.7$ with $\Delta z \approx 0.1$. This survey leads to a new estimate of the star formation rate density at $z \approx 5.7$, $\sim 1.2 \times 10^{-3} h_{0.7} M_\odot$ yr^{-1} Mpc^{-3}. It is also noted that this NB816 survey was used to investigate field Hα emitters at $z \approx 0.24$ [7].

Among their 20 LAE candidates, two objects were confirmed star-forming galaxies at $z = 5.655$ and $z = 5.687$ from their follow-up optical spectroscopy made with FOCAS on Subaru and/or ESI on Keck II. LAE J1044−0130 is identified as a probable superwind galaxy at $z = 5.687 \pm 0.002$ [2]. Its emission line profile is strongly truncated at wavelengths blueward shortward the line peak while shows red-wing emission. The observed broad line width, FWHM (full width at half maximum) $\simeq 340$ km s^{-1} as well as the red wing emission suggest that this object is experiencing the superwind activity. The emission-line morphology appears to show a triangle shape. This may be also interpreted in terms of the superwind activity.

LAE J1044−0123 is identified as a star forming galaxy at $z = 5.655 \pm 0.002$ with a star formation rate of $\sim 13\ h_{0.7}^{-2}\ M_\odot$ yr^{-1} [26]. Remarkably, the velocity dispersion of Lyα-emitting gas is only 22 km s^{-1}. Since a blue half of the Lyα emission could be absorbed by neutral hydrogen gas, perhaps in the system, a modest estimate of the velocity dispersion may be ~ 44 km s^{-1}. Together with a linear size of 7.7 $h_{0.7}^{-1}$ kpc, we estimate a lower limit of the dynamical mass of this object to be $\sim 2 \times 10^9 M_\odot$. Therefore, LAE J1044−0123 seems to be a star-forming dwarf galaxy (i.e., a subgalactic object or a building block).

[3] also made a unique deep survey for LAEs at $z \sim 5.8$ using an intermediate-band filter centered at $\lambda_c \approx 8270$ Å with $\Delta\lambda_{\mathrm{FWHM}} \approx 340$ Å (i.e., the spectroscopic resolution is $R \approx 23$) during the same observing run as that of [2]; see for details of this intermediate-band filter system [25], In this survey, they found four Lyα-emitter candidates from the intermediate-band image ($z \approx 5.8$ with $\Delta z \approx 0.3$); see also [6] for a similar survey for LAEs at $z \simeq 3.7$ using another intermediate-band filter IA 574.

In the above LAE survey, they observed a sky are surrounding the high redshift quasar, SDSSp J104433.04−012522.2 at $z = 5.74$. They found a foreground lensing galaxy with $m_B(\mathrm{AB}) \approx 25$, located at 1.9 arcsec southwest of the quasar [21]. Its broad band color properties from B to z' suggest that the galaxy is located at a redshift of $z \sim 1.5$ - 2.5. Since the counter image of the quasar cannot be seen in our deep optical images, the magnification factor seems not so high. Our modest estimate is that this quasar is gravitationally magnified by a factor of 2 ;see also [31].

3   Concluding Remarks

The Hubble Space Telescope and 8-10m class optical telescopes have been contributing to the progress in deep searches for high-z galaxies. Although the

Subaru Telescope came later to this research field, as we see above, it is also powerful to search for high-z galaxies as well as the other 8-10m class telescopes.

Up to date, approximately several tens of LAEs beyond $z = 5$ have already been identified spectroscopically. However, we still need any systematic deep surveys for such LAEs to understand the whole history of cosmic star formation in the early universe. In particular, one of important things related to LAEs is to construct reliable Lyα luminosity functions of LAEs as a function redshift and the compare them UV luminosity functions; see for recent progress, [2], [10], & [19].

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